Frequency Hopping CDMA for Flexible Third Generation Wireless Networks

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Abstract

Frequency Hopping Spread Spectrum (FH-SS) has found a number of applications in cellular systems, wireless local loop, and wireless local area networks. In this paper, the suitability of Slow Frequency Hopping Code Division Multiple Access (SFH-CDMA) is characterised, for application in third generation wireless communications. An FH architecture displays inherent frequency diversity, and consequently is resilient to the effects of intersymbol interference arising from significant time dispersion in the channel. Furthermore, interference diversity of FH-CDMA results in a robust air interface technique. It is demonstrated that FH-CDMA can support the medium rate service bearers required for UMTS and PCS, whilst providing high cellular capacity in the urban environment.

1 Introduction

The deployment of mobile communications is rapidly expanding throughout the world. The pressure on existing capacity, coupled with the desired enhancement of services, is prompting the development of new and efficient multiple access technologies. The next generation of high capacity wireless communication must offer a range of services, providing high quality at a low cost. The aim of this paper is to assess the suitability of Slow Frequency Hopping Code Division Multiple Access (FH-CDMA) as an air interface technique for flexible future wireless networks.

Recent research considering CDMA for third generation wireless networks has been largely aimed towards the use of the Direct Sequence (DS) spreading technique [1], and consequently commercial applications of Frequency Hopping (FH) have received less attention. Analytical work [2] has shown that the claimed advantages of DS can also apply to FH-CDMA networks when evaluating the relative performance for Personal Communication Systems (PCS), Universal Mobile Telecommunications System (UMTS) and International Mobile Telecommunications system (IMT-2000). Furthermore, the acceptance of frequency hopping as a proven technology in current digital systems, such as the Global System for Mobile communications (GSM) [3], has provided additional encouragement for the development of FH-CDMA architectures. Investigations of the mobile environment indicate that the short term statistics of the channel are improved with frequency hopping [4]. FH performance is largely independent of Doppler frequency, which is particularly important in applications with a link which is stationary or operating at a low velocity, such as wireless local loop and wireless LAN. It is possible to exploit the improvement in the hopped channel with interleaving and coding, or an Automatic Repeat Request (ARQ) protocol [5].

It is proposed that the inherent *frequency diversity* of an FH system can be exploited to mitigate the effects of the wideband channel, facilitating the transmission of high-speed data rate applications. Furthermore, the interference diversity of FH-CDMA results in robust and efficient multiple access. In a practical scenario, it is likely that high data rate bearers will undergo the effects of both co-channel interference and intersymbol interference, arising from time dispersion in the channel. Consequently, both effects are modelled in the analysis of the cellular capacity of an FH-CDMA network.

2 Simulation Method

The results presented within this paper are obtained employing a set of simulation models with standard urban channel impulse responses [6]. The typical urban channel is characterised by a RMS delay spread of $1.026\mu s$ and a coherence bandwidth of 74.41kHz. Consequently, a system with a baud rate in excess of approximately 75kbaud will experience errors due to *frequency selective fading* [7]. A multi-user simulation scenario was applied, using a Monte Carlo approach. The network topology comprises a central base station, surrounded by 3 rings of interfering base stations, arranged in a hexagonal omni-cell pattern. Mobiles are positioned randomly within the network coverage area, and are connected to the base station with the highest link power (incorporating both attenuation and shadowing). The up-link cellular environment parameters are characterised in table 1. The cellular capacity model incorporates the effects of cell loading, voice activity, and propagation characteristics.

Parameter	Specification
Path Loss Coefficient (α)	4
Shadowing Standard Deviation (σ_{log})	8dB
Voice Activity Factor (ϑ)	0.5
Handover Margin (Δ_{HO})	0dB
User Bit Rate, Voice (R_{voice})	8kbps
User Bit Rate, Data (R_{data})	64-512kbps
Acceptable Voice BER	$\leq 10^{-3}$
Acceptable Data BER	$\leq 10^{-9}$
Acceptable Data Throughput	≥ 0.5
Outage Probability (P_O)	1%

Table 1: Up-link Cellular Scenario

3 Link Configuration

The system architecture employed in this paper is relatively simple. It is proposed that acceptable quality-of-service can be achieved without the complexities of equalisation, or a DS-CDMA approach. Similar to previous research in the field, a coherent QPSK system is adopted [8]. In particular, a higher hop rate facilitates exploitation of the inherent advantages of the hopped channel. The studies contained within this paper include the characterisation voice transmission, employing a half-rate convolutional codec and full interleaving up to the specified limit for intelligible speech. Furthermore, the system can be configured for the transmission of data, when transit time requirements are less stringent, and consequently an Automatic Repeat Request scheme is employed.

Parameter	Specification
Modulation	QPSK
Detection	Coherent
Filtering	Raised Cosine (roll-off 0.55)
AWGN	none
Diversity	second order, MRC
Hop Rate	500hps
Hop Frequencies	16
Channel Separation	Ideal
Coding & Interleaving	1/2 rate convolutional
Interleaving Depth	$\leq 40ms$
ARQ	Selective Retransmission, retransmission time=3
Error Detection	(106,128) BCH

Table 2: Link Configuration

4 The Effect of Wideband Fading

It is proposed that the frequency diversity possessed by Frequency Hopping Spread Spectrum can afford inherent resilience to the effects of the wideband channel, facilitating high speed data transmission. In this analysis, wideband fading is assumed to be the dominant error mechanism. The time dispersion of the channel is characterised employing RMS delay spread normalised to the symbol period [9].

4.1 Frequency Diversity

The advantages which accrue to a frequency-hopped architecture in the wideband channel are due to the randomisation caused by hopping. The long term narrowband statistics are unaffected by hopping, whereas the short-term statistics are improved [4]. In specific terms, the advantage of a frequency-hopped system in a wideband channel arises since the *instantaneous* RMS delay spread [9] observed by the system is randomised. Ideally, each hop frequency will have uncorrelated fading, and will therefore exhibit uncorrelated instantaneous dispersion statistics. Consequently, the duration of error bursts which occur due to wideband fading are likely to be confined to the length of a hop period.

4.2 System Performance

4.2.1 Voice Link

In a Slow Frequency Hopping system, each symbol of a particular codeword can be transmitted on an uncorrelated hop frequency, resulting in *codeword diversity* and maximising the efficiency of any Forward Error Correction (FEC). In the case of an interleaved system which does not employ hopping, it is likely that the symbols of a given codeword will experience correlated fading, especially at low mobile velocity.

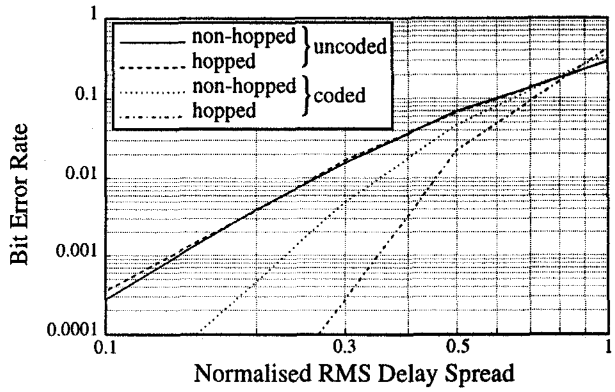

Figure 1: BER vs. Normalised RMS Delay Spread for Hopped and Non-hopped Systems

The results presented in figure 1 indicate that FH and conventional systems will experience identical uncoded performance, since hopping does not alter the long term statistics of the channel. However, there is an improvement associated with FH-SS, since the short term statistics are improved, and consequently interleaving and coding are more effective. In this study, an FH system can tolerate an RMS delay spread of 0.35 when normalised to the symbol rate, as compared to 0.23 without hopping. In a typical urban channel, an FH system can therefore support a raw data rate of 680kbps with a quality criterion of BER less than 10^{-3}.

4.2.2 Data Link

An outage is likely to arise when the instantaneous dispersion becomes significant (as characterised by instantaneous RMS delay spread). In the case of an FH ARQ system, retransmission of a packet can occur on an uncorrelated hop frequency, which is likely to result in error-free reception. A non-hopped ARQ architecture is limited in effectiveness, since the coherence time experienced will be determined by the velocity of the mobile.

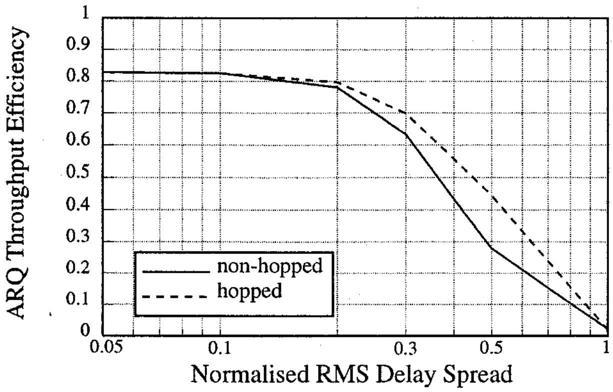

Figure 2: ARQ Throughput Efficiency vs. Normalised RMS Delay Spread

As illustrated by figure 1, frequency hopping will not alter the uncoded statistics of the system. The advantages associated with a frequency-hopped ARQ approach become apparent when the throughput efficiency is examined, as shown in figure 2. Throughput efficiency is defined as the ratio of useful throughput to raw data rate. FH-ARQ demonstrates significant performance improvement over a non-hopped approach, at a Doppler frequency of 6Hz. For example, if a throughput of 0.5 is considered acceptable, FH can tolerate a normalised RMS delay spread of 0.45, as compared to 0.36 without hopping. At higher Doppler frequencies, the ARQ performance of a non-spread spectrum system will improve. However, FH can provide throughput efficiency independent of mobile velocity.

5 FH-CDMA in Multi-user Interference

In the analysis of Frequency Hopping CDMA as an air interface technique, it is important to characterise the capacity of the system. An interference model was developed and employed to characterise a flexible set of service providers, incorporating the effects of co-channel interference and intersymbol interference. Consequently, it is possible to determine which of the PCS service criteria can be fulfilled, whilst providing acceptable capacity and quality.

5.1 Interference Diversity

A frequency-hopped mobile link experiences a sampled version of both the channel fading characteristic and any interference which co-exists in the spreading bandwidth. A given FH link will only suffer the effects of a significant interferer once in a particular hop sequence. In this way Frequency Hopping Spread Spectrum provides inherent resilience to the effects of interference, referred to as *interference diversity.* The entire system will experience composite interference, which is the mean of the interference experienced in the interleaved frame, referred to as *interference averaging.* Furthermore, the amount of averaging experienced is called the *interference diversity factor* by Baier et al [10].

Due to interference diversity, the symbols within an interleaved codeword will experience uncorrelated fading, resulting in the efficiency of any coding scheme being maximised. Alternatively, the throughput of an Automatic Repeat Request (ARQ) scheme can be improved. The enhancement in performance results from the coherence time, or channel memory, becoming fixed in the frequency-hopped channel [4]. Interference diversity in an FH-ARQ system provides uncorrelated interference for each packet retransmission.

	Voice (FEC)	Data (ARQ)
non-hopped	6.95dB	7.74dB
hopped	5.72dB	5.91dB

Table 3: Required C/I Thresholds

To demonstrate the improvement associated with a frequency hopping approach, table 3 summarises the results from an interference-limited simulation study, indicating the required carrier-to-interference ratio for acceptable quality of service. This system is operating at a low Doppler frequency of 6Hz, and non-hopped performance will improve at higher velocities.

5.2 Comparison of DS and FH-CDMA Capacity

Initially, the capacity performance of DS and FH-CDMA are analysed in a network supporting voice links only. In this case, the network is interference limited, and time dispersion is negligible. The DS-CDMA architecture is based on the approach adopted by Sköld et al [8]. A single voice channel is employed with a bit rate of 8kbps, and a spreading bandwidth of 1MHz, resulting in a processing gain of 21dB. The required E_b/N_0 threshold for a BER less than 10^{-3} is 7dB. Consequently, a carrier-to-interference threshold of greater than -14dB is required [8].

The Frequency Hopping CDMA architecture employs orthogonal hopping within a cell, resulting in no intra-cell interference. Furthermore, adjacent cells utilise unique hopping patterns, resulting in randomisation of observed interference. An interference diversity factor of 8 is utilised. Employing the C/I threshold included in section 5.1 it is possible to calculate the probability of the system being in outage (shown in figure 3).

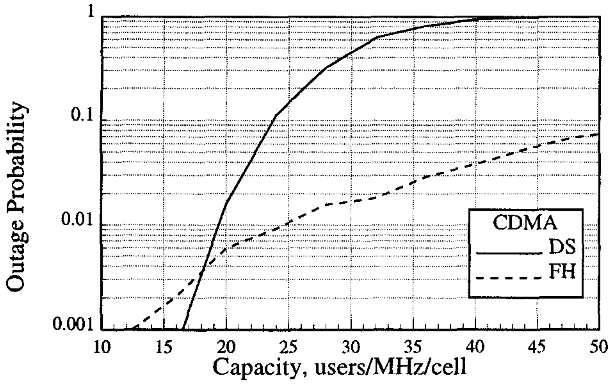

Figure 3: Outage Probability for DS and FH-CDMA

Employing an outage probability of 1%, the DS and FH system provide reasonably similar capacity, with a loading level of 19 and 25 users/MHz/cell respectively (from figure 3). This performance is comparable to the results obtained by other authors [8,10]. Both CDMA systems exhibit a *soft capacity* limitation, where more users can be added to the network, at the expense of overall quality-of-service. However, in the case of FH, the degradation in quality is more gradual, and consequently more users can be added for a comparable decrease in performance. For example, at a link availability of 5% [2], DS will support 22 users/MHz/cell, compared to 44 for an FH system.

5.3 Flexible Service Provision

To further characterise the performance of FH-CDMA as an architecture for flexible PCS, the capacity limitations of a number service bearers are characterised, at 64, 256 and 512kbps. In each case, the acceptable carrier-to-interference threshold for voice transmission was determined, incorporating the effects of intersymbol interference. The required C/I thresholds are included in table 4, for the quality-of-service metrics described in table 1. It can be seen that the impact of intersymbol-interference at high data rates significantly degrades performance.

Sevice Bearer	Voice C/I Threshold (dB)	Data C/I Threshold (dB)
64	5.51	5.95
256	5.72	6.80
512	9.61	9.41
1024	∞	∞

Table 4: Required C/I Thresholds for a Variety of Service Bearers

5.3.1 Voice Network

Results of outage analysis for voice channels on a variety of FH bearers are presented in figure 4. The simulation study indicates that the best performance is exhibited by the lower data rate bearers, at 64 and 256 kbps, supporting 25 and 21 users/MHz/cell with acceptable quality criterion. The capacity for a bearer at 64kbps is identical to the performance of a single narrowband voice channel, shown in figure 3. Furthermore, frequency hopping the system mitigates the effects of wideband fading so that a high quality system can be supported at 256kbps (with normalised RMS delay spread of 0.262), with a cellular capacity of 21 users/MHz/cell for a voice network. The highest data rate bearer shown in figure 4 demonstrates a poor capacity, due to the combination of frequency selective fading and co-channel interference.

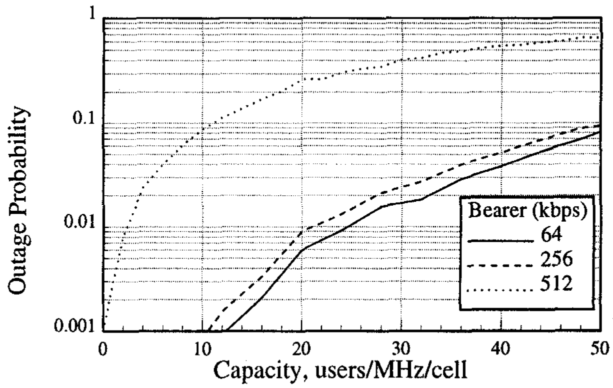

Figure 4: Capacity of a Variety of Voice Bearers

5.3.2 Data Network

The capacity analysis of a frequency-hopped data transmission architecture is demonstrated in figure 5. In this case, the figure demonstrates the utilisation over the entire network, in terms of raw data rate capability per cell against useful, uncorrupted received data. The "ideal" bearer demonstrates performance when all packets are received correctly, and indicates the overhead associated with the error detection scheme. With realistic service providers, throughput efficiency reduces as the loading level increases, due to the higher level of interference. This effect is especially noticeable for the higher rate bearers, where the errors due to interference are augmented by frequency selective fading.

In a practical scenario, a user would be allocated a portion of the overall available data capability. Since the system is frequency hopped and exhibits interference averaging, each user experiences the indicated throughput efficiency on average. In this analysis, the two lower speed data bearers meet an acceptable throughput efficiency of 0.5 up to the maximum cellular capacity. Service provision at 512kbps does not meet this quality criterion when the capacity exceeds approximately 0.55 Mbps/MHz/cell.

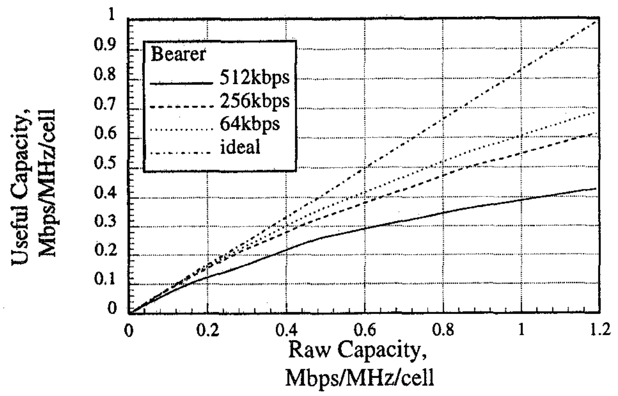

Figure 5: Overall Performance of a Variety of Bearers

6 Conclusions

A conventional non-hopped system can produce error bursts of significant duration, due to wideband fading or co-channel interference. The randomising effect of frequency hopping limits the impact of error bursts. Furthermore, it is possible to implement interleaving or ARQ to exploit the inherent advantages of the frequency-hopped channel. Improvement in quality-of-service is more significant at low Doppler frequencies, when significant bursts of errors occur in a non-hopped system. Consequently, FH is particularly appropriate when the channel is slowly changing or stationary, which often occurs in wireless LAN and wireless local loop techniques. The nature of FH-CDMA eases the frequency planning requirements in a cellular network, since the interference pattern is randomised each hop, and consequently no one interferer can dominate [3].

Comparison of Direct Sequence and Frequency Hopping CDMA indicates similar voice channel capacity performance. In addition, FH-CDMA displays a greater soft capacity facility than DS-CDMA, which is important in the provision of a flexible cellular system. The suitability of FH-CDMA in the provision of a flexible set of service bearers is characterised in section 5.3. In particular, data services often require high bit rates, resulting in a combination of co-channel interference and wideband fading. It is shown that an FH-CDMA configuration can support data rates in the order of 256kbps in a typical urban macrocell, with acceptable user capacity. In less time dispersive channels (such as indoor or microcellular environments) FH-CDMA can be employed to provide a higher data rate capability.

Evaluation of macrocellular capacity has indicated that an FH-CDMA system in an urban environment cannot support the high bit rate services for PCS. However, the technique can suport acceptable quality of service for medium rate service bearers, in the order of 256kbps. Frequency Hopping CDMA can be employed as an efficient, simple, and robust air interface scheme for the provision of low to medium data rate services in a third generation wireless network.

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